APPLICATION OF THE V-GAMMA MAP TO VEHICLE BREAKUP ANALYSIS

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ABSTRACT

The V-Gamma map consists of all possible pairs of speed (V) and flight path angle (Gamma) at atmospheric entry interface for accidental Earth reentries resulting from steady misaligned burns, incomplete burns, or no burn. The original V-Gamma Map software, which was developed twenty years ago in FORTRAN on the UNIVAC computer, has been reproduced in a MATLAB environment. Software design and implementation based on the functional requirements produced a user-friendly code. The manual post-processing in the original V-Gamma Map was also automated. The new V-Gamma Map software was validated by comparing against the old code, and had been successfully applied to the MER mission. In the vehicle breakup analysis of the MER mission, the V-Gamma Map was used as a pre-processor to provide the initial speed and flight path angle for accidental out-of-orbit reentries, and points about the V-Gamma Map were considered in order to bound the possible reentry scenarios.

INTRODUCTION

For a launch involving RTGs (Radioisotope Thermoelectric Generator) or LWRHUs (Light Weight Radioisotope Heater Unit), it is customary to perform analyses of possible accidents during the launch, particularly accidents which can result in the RTGs or the LWRHUs reentering the Earth's atmosphere. A useful starting point in such analyses is a so-called "V-Gamma Map", which is the envelope of all the speeds, V, and flight path angles, gamma, with which the vehicle can reenter the Earth's atmosphere. This paper develops the V-Gamma map for the Mars Exploration Rover (MER) mission. Because the envelope describes the full range of V and gamma pairs that can arise, it is calculated by assuming a "Steady Misaligned Burn" (SMB), where the vehicle maintains a constant wrong heading in space during the burns and the intermediate staging.

In this paper, the original V-Gamma Map software (Ref. 1), which was developed twenty years ago in FORTRAN on the UNIVAC computer, is reproduced in a MATLAB environment. Software design and implementation based on the functional requirements produces a user-friendly code. The manual post-processing in the original V-Gamma Map is also automated.

In the vehicle breakup analysis of missions involving RTGs or LWRHUs, the V-Gamma Map is used as a pre-processor to provide the initial speed and flight path angle for out-of-orbit reentries, and points about the V-Gamma Map are considered in order to bound the possible reentry scenarios.

HISTORY AND EVOLUTION

A requirement prior to launching an interplanetary spacecraft carrying substances that may pose a special hazard if there is an accident (e.g., plutonium) is that all foreseeable faults possibly leading to reentry of the spacecraft or part of the launch vehicle be analyzed to determine the probability of any hazard. One important tool in these analyses is the V-gamma map, in which all the onboard propellant is assumed to be burned in an arbitrary constant single wrong direction, thereby determining the full possible range of entry speed and entry angle that the reentry vehicle can acquire in the so-called Steady Misaligned Burn (SMB). Thus, the V-gamma map can be considered the outer envelope of all possible pairs of reentry speed and angle pairs. We recognize that there is a relatively small probability that a reentry following an accident may fall on the boundary, but the outer boundary is useful as being the limit that can occur.

Typically a spacecraft embarking on an interplanetary journey is first placed in an intermediate "park" orbit just above the Earth's atmosphere, and begins further burns which finish in placing the spacecraft on its correct departure path to the planet. Typically, also, the launch vehicle performs several burns, frequently using both liquid and solid motors, with staging of the empty motor case before the next burn. Historically it was the custom to generate the V-gamma map by performing many trajectories on a Monte Carlo basis, beginning in the parking orbit and performed in a randomly chosen steady wrong direction, thus building up a set of entry V and gamma values which would eventually determine a boundary if enough cases were run. Because the SMB cases resulted in reentry at various times during the burns from park orbit, one could determine the relative probability of several outcomes. The basic outcomes for these SMB are of six types:

1) **Hyperbolic escape (HES)**: The spacecraft has reached hyperbolic speed and is not on a path that enters the atmosphere. It includes the desired special case of a successful launch on target. The hyperbolic escape is of medium probability.

2) **Orbit decay reentry (DEL)**: The perigee of the final orbit is above the atmosphere, so that reentry occurs after a period of orbit decay. The circular orbit decay (COD) is a single point at near circular speed with near zero flight path angle. Reentry may occur one or two weeks later. With a shallow reentry angle, there may be multiple skip-outs before the spacecraft is captured into atmospheric reentry. The orbit decay reentry is of relatively low probability.

3) **Powered reentry (PWE)**: The reentry occurs while the burns are in progress, and the spacecraft has not separated from the launch vehicle. The powered reentry is of relatively high probability.

4) **Prompt reentry (ELP)**: The burns have finished prior to reentry but the vehicle is then on a downward path approaching a perigee within the atmosphere. The prompt elliptic reentry is of relatively low probability.

5) **Delayed reentry (ELD)**: The vehicle is on an upward path at the end of the burns and will reenter the atmosphere after passing though an apogee. Generally, the delayed reentry is of the highest probability.

6) **Prompt hyperbolic reentry (HP)**: The vehicle has an escape speed but will reenter the atmosphere and may exit and fall into the HES or ELD categories. The prompt hyperbolic reentry is of the lowest probability.

One problem in the Monte Carlo analysis is the large number of random cases that are necessary to fill in the details of boundaries between the categories. JPL engineers discovered a useful concept about twenty years ago that allow added details on the category boundaries to be readily determined. This concept was to map the cases in terms of the original steady wrong direction, expressed as a cone angle (A) and a clock angle (B) from the original park orbit velocity direction as shown in Figure 1. It turns out that in the departure plane the categories fall in clear separate areas, and this allows (A, B) points to be added readily to clarify boundaries between categories. It also allows a simple geometrical computation of the relative probabilities of the six categories on a random basis. In addition, it allows plots of reentry time and reentry angle of attack of the vehicle performing a PWE reentry, and these are useful in computing the trajectory of a powered reentry in the atmosphere. The computer program coding this concept allows three burns and two coast periods, controlled on a time-from-start-of-burn basis. This code has now been automated to plot these maps, given the initial park orbit and launch vehicle burn parameters, and the number of random points desired in the computation. For example, a grid of 2 degrees in cone angle A (0 to 180 deg) and in clock angle B (+90 to –90 deg) gives 8100 points. The choice of which category the outcome will fall in is made by evaluating the semi-major axis, the path angle and altitude of the trajectory during, and at the end of the burn.

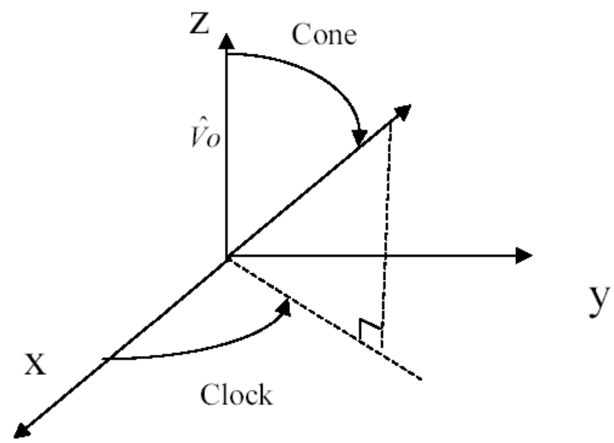

Figure 1. Definition of Cone and Clock Angles

APPLICATION OF V-GAMMA MAP TO VEHICLE BREAKUP ANALYSIS

The purpose of vehicle breakup analysis is to determine the impact points of spacecraft and launch vehicle debris with emphasis on the RTGs and the LWRHUs. Accidental Earth reentry includes those failures which may arise both in the departure from park orbit (out-of-orbit reentry) and in the ascent to park orbit (sub-orbital reentry). In the vehicle breakup analysis of missions involving RTGs or LWRHUs, the V-Gamma Map is used as a pre-processor to provide the initial speed and flight path angle for out-of-orbit reentries, and points about the V-Gamma Map are considered in order to bound the possible reentry scenarios. These points are used as initial conditions in the propagation of the reentry trajectory. Breakup of a spacecraft or launch vehicle component occurs when integrated heating and/or g-load exceed some failure criteria. If the RTG or the LWRHU fails and gets released, propagation proceeds by following the released RTG/LWRHU to a ground or ocean impact.

NEED FOR A NEW SOFTWARE AND AUTOMATION

The original V-Gamma Map software discussed above was written in FORTRAN and run on the UNIVAC operating system. Once the trajectory propagations were performed to produce the possible entry speeds and flight path angles, plots were then made manually to generate the V-Gamma maps. The software developer was the chief analyst and sole user of this software program, and no document existed for the algorithm description, software design, or user's guide. Thus, it was essential to reproduce the capabilities of the legacy software with thorough documentation such that the V-Gamma Map analysis tool is maintainable for the future generation of analysts. Furthermore, the software should be user-friendly, and post-processing should be automated to facilitate the generation of plots.

FUNCTIONAL REQUIREMENTS

Before proceeding with the software development for the V-Gamma Map (VG), it was necessary to capture the functional requirements of the analysis tool. The high-level requirements included (ref. 2):

1. The VG shall function as a stand-alone MATLAB program.
2. The VG shall allow multiple finite burns.
3. The VG shall allow two options in the determination of the thrust misalignment angles:
    a. Via random number generator
    b. Step through cone and clock angles specified by user
4. The VG shall categorize each V-gamma pair as one of the following six classes of reentry:
    a. Hyperbolic escape (HES)
    b. Prompt elliptic reentry (ELP)
    c. Delayed elliptic reentry (ELD)
    d. Powered re-entry (PWE)

e. Decay of an initial ellipse (DEL)
f. Prompt hyperbolic reentry (HP)

5. The VG shall calculate the weighting factor in terms of percentage of probability for each class of reentry.
6. The VG shall provide an automation routine for the generation of the V-gamma map.
7. The VG shall provide the following output plots:
   a. V-gamma map for all 6 classes of reentry
   b. Departure plane map for different classes of reentry relative to cone and clock angles
   c. Time of entry in powered reentries relative to cone and clock angles
   d. Angle-of-attack at entry in powered reentries relative to cone and clock angles
   e. Detailed V-gamma map for powered and prompt reentries
8. The VG shall provide the following output tables:
   a. Time history of events (i.e. finite burn and coast) and mass
   b. Relative probability of each class of reentry

SOFTWARE DESIGN, IMPLEMENTATION AND TESTING

The V-Gamma software is coded in the MATLAB scripting language. Figure 2 below depicts the main components of the software (ref. 3):

1. Input GUI
2. Output options GUI
3. Simulation loop
4. Post-processing

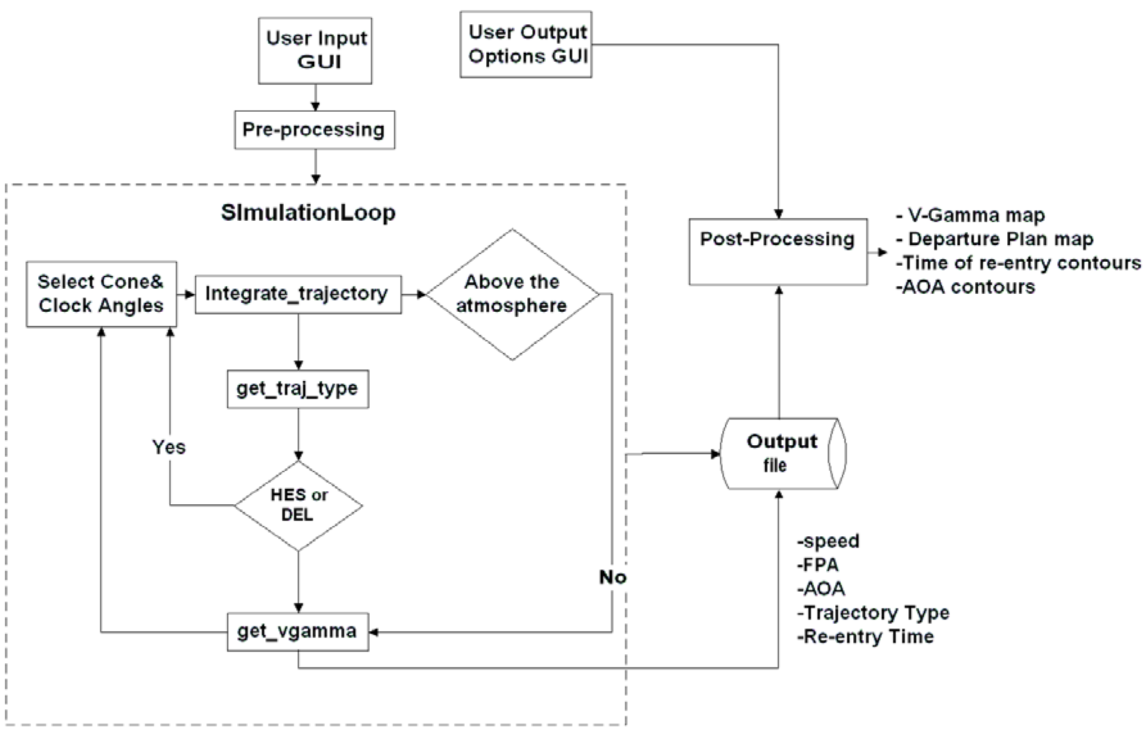

Figure 2: Block diagram of the V-Gamma software

User Input GUI

The user enters the following parameters in the input GUI (ref. 4):

1. Initial conditions of the parking orbit (apogee and perigee).
2. ISPs of up to three burns.
3. Mass of the spacecraft before and after each burn/coast sequence: m1, m2, …, m6 (Figure 3).
4. Duration of the burn and coast sequences (Figure 3).
5. Specification of the range of cone and clock angles.
6. Step-sizes of the cone and clock angles in the specified range.
7. The number of pairs of cone and clock angles if they are selected randomly from the specified range.

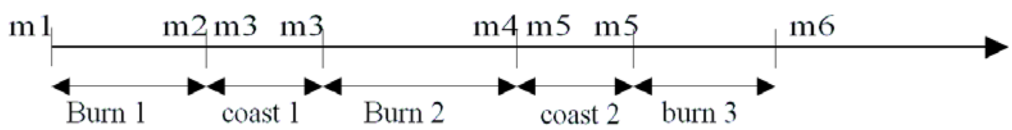

Figure 3: **Time-line of Events**

Simulation Loop

In the simulation module, the software loops through the pairs of cone and clock angles in the specified range, either at uniform step-sizes or randomly. If the “random” option is selected, the pairs of cone and clock angles are selected from a uniform random distribution of the (spherical) surface spanned by the range of these angles. A brief description of the functions that are used in the simulation loop is now given.

1. *Integrate_trajectory*: This function integrates the trajectory during the burn and coast intervals. If the spacecraft reaches the atmosphere before the end of the last burn, the integration is terminated and the trajectory is tagged as a Powered Entry (PWE).
2. *Get_traj_type*: This function tags the trajectory corresponding to a pair of cone and clock angles as one of the following five types: (1) Hyperbolic Escape (HES), (2) Elliptic Prompt reentry (ELP), (3) Elliptic Delayed reentry (ELD), (4) Decay of an Ellipse (DEL) and (5) Hyperbolic Prompt reentry (HP). The trajectory type is determined from the eccentricity, periapsis and the radial speed at the end of the burns.
3. *Get_vgamma*: Computes speed, flight path angle (FPA), angle-of-attack (AOA) and time of re-entry analytically.

Post-Processing and the Output Options GUI

The output options GUI calls the post-processing function that generates the maps (V-gamma and Departure Plane) and the two contours plots corresponding to powered reentries (Reentry time and Angle of attack). In addition, the probability of each class of reentry are computed and displayed.

Software Verification

The software was validated by comparing the results against the legacy FORTRAN code using the same input parameters (ref. 5). In addition we have made sure that both codes use the same constants, such as the altitude of the atmosphere, radius of the Earth, gravitational constant, etc. The results that were compared were: (1) Trajectory types, (2) Reentry parameters (speed, flight-path-angle, time of reentry and angle-of-attack), (3) Probability of each class of reentry, (4) The V-Gamma and the departure plane maps. All results were verified to be within the precision of the two computers, the old and the new codes run on.

MARS EXPLORATION ROVER (MER) MISSION

NASA's twin robot geologists, MERA and MERB, were launched on June 10 and July 7, 2003, respectively, in search of answers about the history of waters on Mars. The two rovers will be delivered in landing craft to separate sites on Mars in January 2004. The mission's scientific goals are to search for and characterize a wide range of rocks and soils that hold clues to past water activity on Mars.

MERA was launched using a Delta II 7925 launch vehicle, and since MERB required more energy to get to Mars, a Delta II 7925 H was used. After the boost stage (Stage I), two more stages were used to inject the cruise stage into a trajectory to Mars. Stage II fires twice, once to insert the vehicle-spacecraft stack into a low Earth orbit, and then again to provide the required proper Mars alignment and velocity for the third stage and MER. The purpose of Stage III/Star 48 is to provide the majority of the velocity change needed to leave Earth and then inject the spacecraft into a trajectory for Mars.

UTILIZATION IN ACCIDENTAL EARTH REENTRY ANALYSIS IN MER MISSION

The applications of the V-Gamma maps in the Mars Exploration Rover (MER) mission were in the accidental out-of-orbit reentries. The required inputs for the V-Gamma Map were obtained from the Detailed Test Objectives (DTO) trajectories for the two MER spacecraft, MERA and MERB, and are listed below.

Parameters	**MERA June 10 Azimuth 93°**	**MERB July 7 Azimuth 99°**
Initial Apogee (km)	179.16	178.38
Initial Perigee (km)	160.88	159.16
Eccentricity	0.001396	0.001468
First Burn Duration (sec)	125.857	149.566
Second Burn Duration (sec)	87.14	87.14
Coast Duration Between 2 Burns (sec)	90	90
ISP of First Burn (sec)	313.9	313.9
ISP of Second Burn (sec)	292.5	292.5
Mass at Start of First Burn (kg)	6072.439	6830.881
Mass at End of First Burn (kg)	4482.645	4698.925
Mass at Start of Second Burn (kg)	3310.537	3315.046
Mass at End of Second Burn (kg)	1291.599	1296.085

The V-Gamma Map plots for MERA and MERB were similar, thus only MERA plots are presented. The following plots from the V-Gamma Map were obtained for MERA:

1. Possible entry speeds and flight path angles for the various classes of reentry trajectories are given in the V-Gamma Map as shown in Figure 4.
2. The relative probabilities of the different classes of trajectories are given in the pie graph as shown in Figure 5.
3. The departure plane map for the various classes of trajectories as functions of cone and clock angles are shown in Figure 6.
4. The possible entry times relative to the start of the first burn in powered reentries are given in a contour plot as functions of cone and clock angles as shown in Figure 7.
5. The possible entry angles-of-attack in powered reentries are given in a contour plot as functions of cone and clock angles as shown in Figure 8.

Note that the powered reentry and elliptic delayed reentry were of the highest probabilities. Powered reentry may occur as early as 126 seconds at the end of the first burn. The MER mission required relatively lower energy and departure velocity compared to missions to the outer planets. Thus, the spacecraft had a high probability of reentering the atmosphere in the event of a launch contingency.

To perform detailed vehicle breakup analysis, the entry speeds, flight path angles, and angles-of-attack were obtained from the V-Gamma Map for out-of-orbit reentry cases as shown in Table 1. Reentries of high probability were analyzed, including one case of powered reentry, one case of delayed elliptic, and two cases of circular orbit decay. Note that the attitude of the spacecraft at reentry in a COD would be arbitrary, and two angles-of-attack were chosen for detailed analysis.

Table 1. Entry Conditions from the V-Gamma Map for the MER Mission

Case	Cone Angle (deg)	Clock Angle (deg)	Entry Conditions			
			Speed (m/s)	Gamma (deg)	Angle of Attack (deg)	Time of Entry (sec)
Powered Reentry	90	-15	7916	-1.8	78.7	221
Delayed Elliptic	140	60	4946	-16.8	154.4	677
Circular Orbit Decay	N/A	N/A	7803	-0.2	0, 90	N/A

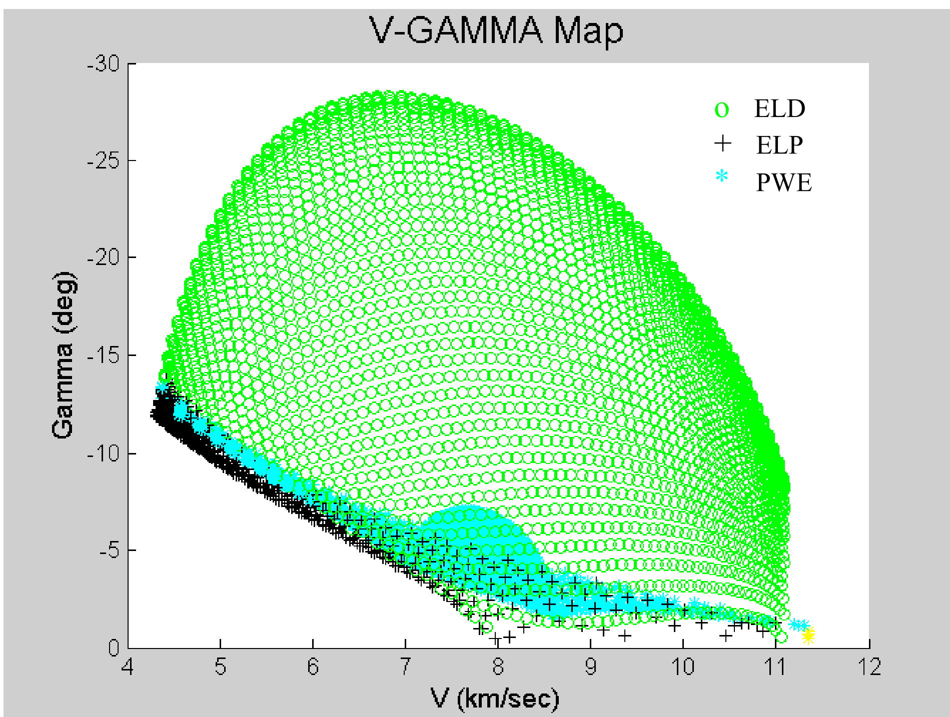

Figure 4: V-Gamma Map for the MERA Mission

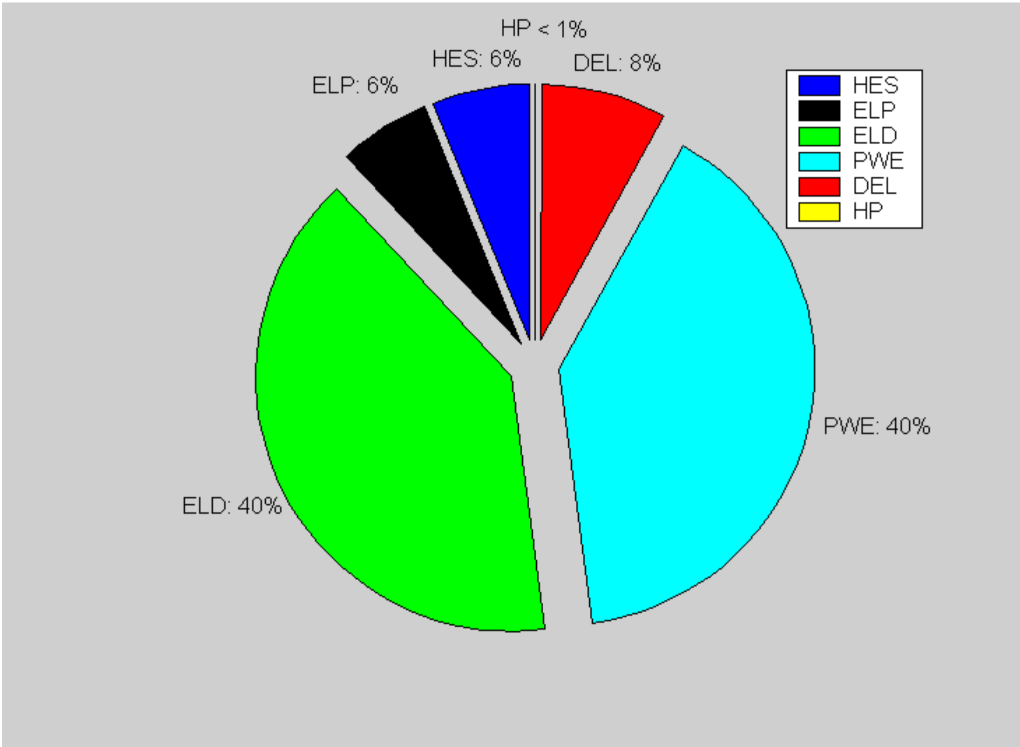

Figure 5: Relative Probabilities for the MERA Mission

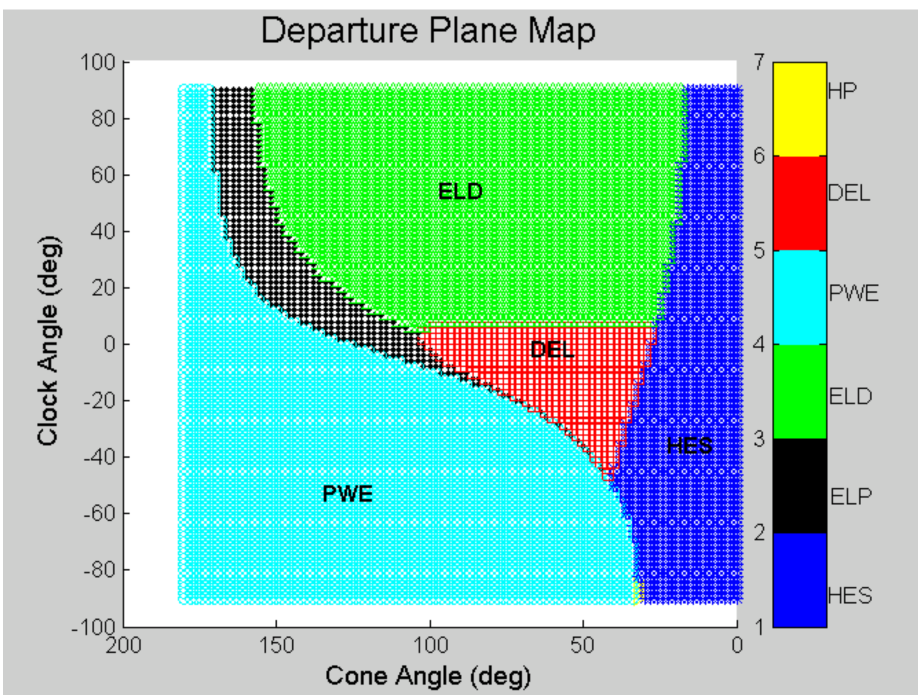

Figure 6: Departure Plane Map for the MERA Mission

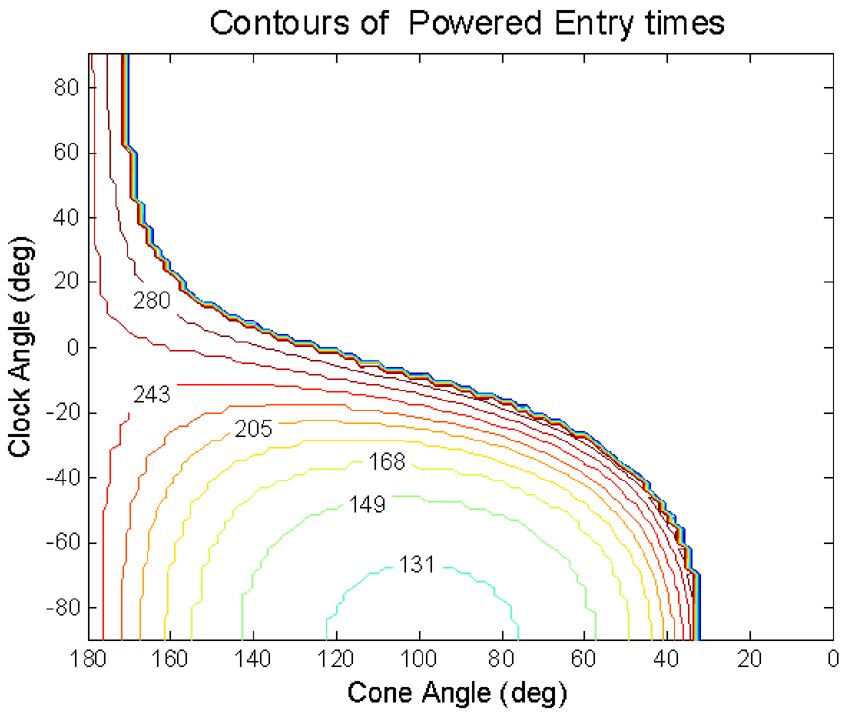

Figure 7: Contours of Powered Entry Times Measured from Stage II Restart for the MERA Mission

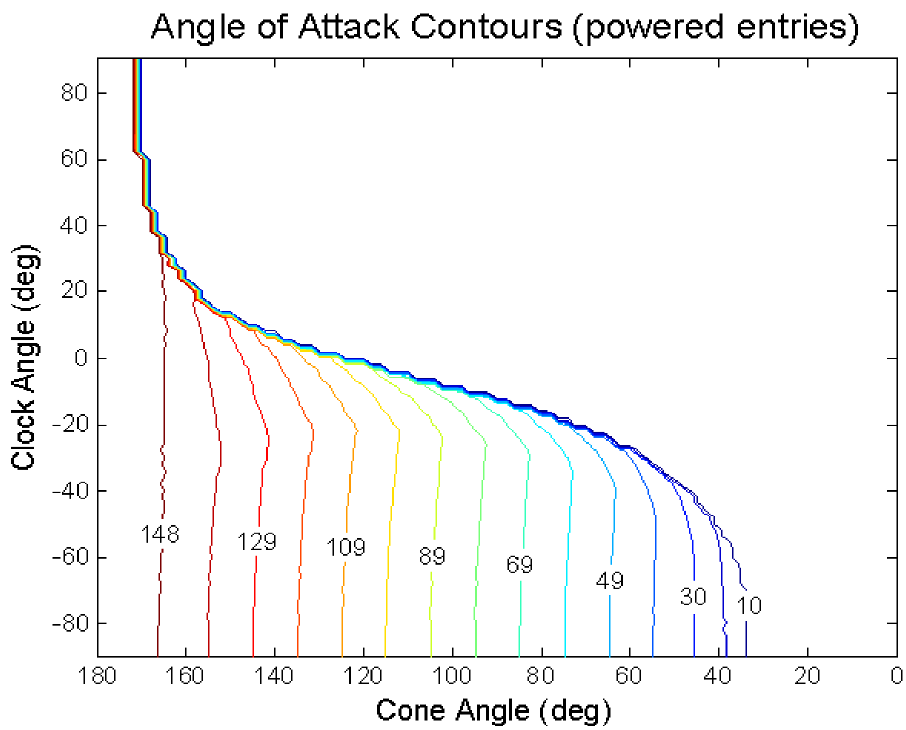

Figure 8: Contours of Powered Entry angle-of-attack for the MERA Mission

CONCLUSIONS

A successful launch to Mars or any other planet must inject the spacecraft into its interplanetary trajectory. Historically, there is a few percentages probability of launch failure that leads to accidental Earth reentry (mostly COD). This includes failures which may arise in the departure from park orbit (out-of-orbit reentry) or in the ascent to park orbit (sub-orbital reentry). This paper has developed the V-Gamma map for the MER mission which is used as a preprocessor to provide initial speed and flight path angle for out-of-orbit reentries due to SMBs.

In the slight probability of an SMB, the MER mission failure categories provided by the V-Gamma map have been addressed. Since the MER mission requires relatively lower launch energy and departure velocity compared to missions to the outer planets, the spacecraft has a relatively higher probability of reentering the atmosphere (mostly ELD as shown in Figure 5). Powered reentry (also high probability) may occur as early as 126 seconds from Stage II restart. Also, due to the lower launch energy, the conditional probability for hyperbolic escape is relatively lower (6 %) than those expected in launches to the outer planets. Finally, as seen in Figure 4, the maximum flight path angle is about -28 degrees (in an ELD category). Lack of very steep reentries indicates that breakup would probably be due to heating more than g-load.

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